ORIGINAL ARTICLE

Are overground or treadmill runners more likely to sustain tibial stress fracture?

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Background: Repetitive high bone strain and/or strain rates, such as those that occur during running, contribute to stress fractures as well as promoting maintenance of or increase in bone mass. Kinematic differences are known to exist between overground and treadmill running and these may be reflected in different bone strains and strain rates during the two running techniques.
Aim: To measure in vivo strains and strain rates in human tibia during treadmill and overground running and determine if there are significant differences in strain and strain rate levels between the two running techniques.
Methods: A strain gauged bone staple was mounted percutaneously along the axial direction in the mid diaphysis of the medial tibia in three subjects, and in vivo tibial strains were measured during treadmill and overground running at 11 km/h.
Results: Axial compression strains ($p<0.0001$), tension strains ($p<0.001$), compression strain rates ($p<0.0001$), and tension strain rates ($p<0.0001$) were 48–285% higher during overground running than during treadmill running.
Conclusions: On the basis of lower in vivo strains and strain rates, treadmill runners are at lower risk of developing tibial stress fractures, but less likely to achieve tibial bone strengthening, than overground runners.

In the 1970s and 1980s, overground running was at the height of its popularity. At that time the extrapolated yearly stress fracture rate for runners was 4.6%.[1] The tibia was the most prevalent site for stress fracture.[2] In the past decade, running as a recreational sport has changed, with an increase in treadmill runners. According to *Runners' World*, 40 million Americans run on treadmills, and 70% of new home treadmill buyers are women.

If competitive runners are excluded, there are many possible motivations for participating in running. These include cardiovascular fitness, "burning calories" to maintain body physique, enhancing bone and muscle strength, and the promotion of a general feeling of health or youth. Ideally one would like to achieve these goals without sustaining overuse injuries or damage to joints. Runners have the option of choosing to do their workouts on a treadmill or overground. Unlike overground running, there is no epidemiological data for overuse injuries caused by treadmill running. In previous strain gauge measurements in humans in vivo, tibial strain and strain rates have been found to be significantly higher during running than during walking.[3–6] Likewise measurement of tibial shock, using bone mounted accelerometers, has shown that the peak tibial shock is higher during running than during walking.[7]

The hypothesis of this study is that tibial strains and strain rates during treadmill running are much lower than during overground running. As repetitive high strains and strain rates contribute to stress fractures,[8] the prevalence of tibial stress fractures in treadmill running would consequently be lower than in overground running.

MATERIALS AND METHODS

Two male members of the research staff (one aged 54 and weighing 82 kg and the other aged 41 and weighing 78 kg) and one female member (aged 23 and weighing 60 kg) were recruited to have measurements of tibial strain in vivo. After receiving an explanation of the goals, risks, and benefits of their participation in the experiment, all subjects gave their informed consent. The experimental protocol was approved by the human rights committee of the Hadassah University Hospital, Jerusalem, Israel and the Ministry of Health of Israel. All subjects were healthy. The men were recreational runners averaging 10 km/week, and the woman played occasional recreational tennis.

In vivo strain measurements

Strain gauged staples made from 3M 16 × 15 mm bone staples (3M Health Care, St Paul, Minnesota, USA) with a Micro-Measurements EA-06-031DE-350 strain gauge (Measurements Group Inc, Raleigh, North Carolina, USA) bonded to

Table 1 Strain and strain rates for each subject during treadmill and overground running

	Strain ($\mu\epsilon$)				Strain rate ($\mu\epsilon$/s)			
	Compression		Tension		Compression		Tension	
Subject	Treadmill	Overground	Treadmill	Overground	Treadmill	Overground	Treadmill	Overground
1	614 (28)	2456 (144)	1243 (26)	1158 (30)	4198 (714)	14538 (1228)	10045 (1387)	9276 (460)
2	417 (2.9)	1967 (97)	687 (24)	998 (46)	2674 (1083)	9211 (664)	6717 (2368)	15925 (1974)
3	959 (25)	1446 (114)	648 (27)	1163 (96)	3168 (111)	14880 (954)	3175 (54)	17289 (237)

Values are mean (SD).

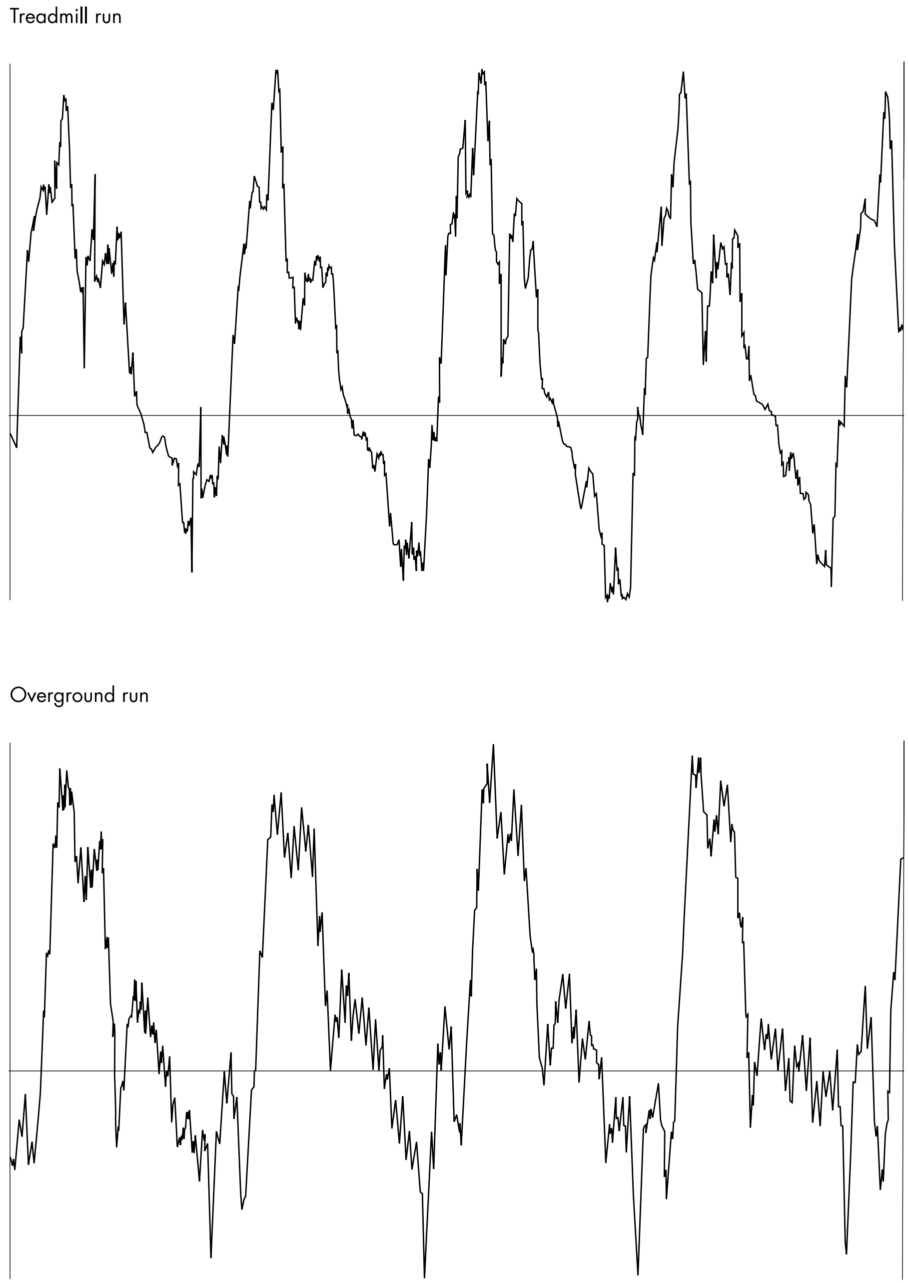

Figure 1 Plot of strains during treadmill and overground running for the second subject.

the undersurface of the staple were used to measure in vivo tibial strains and strain rates.[9] The strain gauges were connected to a ¼ Wheatstone bridge. A strain gauged staple was implanted percutaneously, aligned along the long axis of the bone in the medial aspect of the mid-diaphysis of the tibia in each subject.

Surgical protocol

Surgical implantation of the strain gauged staples was performed on an outpatient basis at the Hadassah University Hospital. Surgical implantation was performed in the morning, and the staples were removed on the same day after completion of the data collection. Prophylactic intravenous cefonicide was given before each operation.

The left leg was prepared and draped at the level of the mid-shaft of the tibia to facilitate placement of the strain gauged staples in the medial aspect of the tibia. The exact level of the mid-diaphysis and the midpoint of the flat medial surface of the tibia were determined. An alignment block for the insertion of the staple was then placed central at this point, and the site of the entrance holes for the staple legs was marked. Local anaesthesia was given at these two points by injection of 1.5 ml 1% lidocaine and 1.5 ml 0.25% buperocaine into the skin, subcutaneous tissue, and periosteum of the tibia. Surgical stab wounds were made in the skin and subcutaneous tissue at each of the two points, and the two entrance sites for the legs of the staples were drilled 4 mm into the tibial cortex with a 1.2 mm diameter drill using an alignment jig and a depth limiting device. The strain gauged staple was inserted into the tibia using a specially made inserter impacter permitting the staple to be driven into the pre-drilled holes to a depth of 4 mm into the cortex. A gauze dressing was placed loosely over the staple.

Strain gauge measurements

Immediately before and after each recording, the strain gauge was zeroed with the subject holding his/her left leg in the air so that it was non-weight bearing. The strain gauge signal was amplified, and the conditioned signal recorded on an FM analogue cassette recorder (TEAC HR10; TEAC Corp, Tokyo,

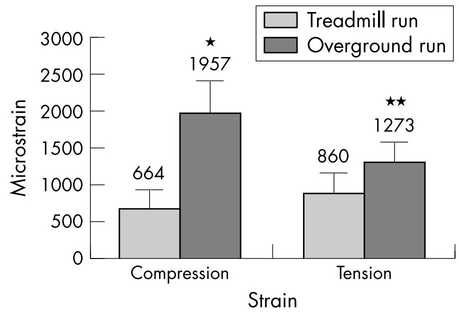

Figure 2 Tibial axial strains during treadmill versus overground running. Bars represent standard deviations. *p<0.0001; ** p<0.001.

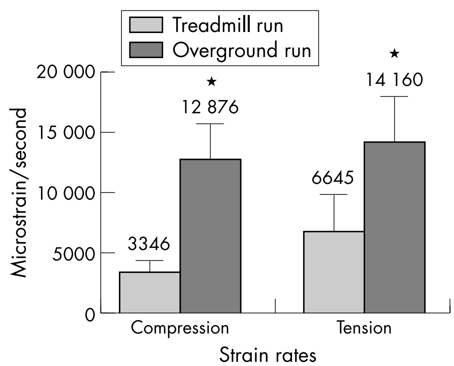

Figure 3 Tibial axial strain rates during treadmill versus overground running. Bars represent standard deviations. *p<0.0001.

Japan). The amplifier and cassette recorder were carried by the subject in a multipouch backpack. Playback was by a separate unit (TEAC MR40; TEAC Corp) connected to a PC, and the data were digitised at 400 Hz. The strain gauged staple strains were calculated from the voltage output using the method described by Ekenman *et al*.[9]

All subjects wore Nike Air Max running shoes for the experiment. Measurements were made while running on a treadmill at a speed of 11 km/h and while free running on asphalt at the same rate set by a timed pacer. The measurements were begun after one minute of running and were made over a 60 second time interval.

Data analysis

The data from the strain gauged staple were processed using a custom written computer program. The digitised amplified signals were low pass filtered at 5 Hz, and the peak axial tension and compression strains and the maximum tension and compression strain rates recorded for each step. The maximum strain rates were calculated by scanning 12 millisecond intervals along the tension and compression strain outputs. Means were calculated for treadmill and free running on the basis of four consecutive strides. The major outcome variables were the means of the peak axial compression and tension strains and maximum compression and tension strain rates for treadmill and overground running. Statistical analysis used the Statistical Analysis System (Cary, North Carolina, USA) for comparing the results for treadmill and overground running using a block analysis of variance, with statistical significance $p = 0.05$.

RESULTS

There were no complications secondary to the surgical implantation of the strain gauged staples. All subjects returned to their normal activities including running within 10 days of surgery.

Table 1 shows the mean strain and strain rates of four consecutive strides for each subject during treadmill and overground running. Figure 1 shows a plot of the strains during treadmill and overground running for the second subject. The ratio of the peak tension strain to the peak compression strain during treadmill running is higher than during overground running. The peak mean tibial axial compression ($p<0.0001$) and tension strains ($p<0.001$) (fig 2) and peak mean tension ($p<0.0001$) and compression strain rates ($p<0.0001$) (fig 3) for the three subjects were significantly higher during overground running than during treadmill running.

DISCUSSION

When non-competitive runners choose between overground and treadmill running, many of their considerations are related to convenience, sociology, and climate. Considerable kinematic differences, however, exist between the two types of running.[10–13] Elliot and Blanksby[10] reported that stride length is decreased, stride rate increased, and the period of non-support is less when running on a treadmill than when running overground. Nigg *et al*[12] observed that subjects plant their feet in a flatter position during treadmill running than during overground running. They found that most of the lower extremity kinematic variables showed inconsistent trends for individual subjects depending on the subject's running style, running speed, and footwear. Treadmill running is for the most part a monotonous repetition of the same body kinematics, whereas overground running can involve frequent changes in direction, pace, and stride length.

This study was designed to evaluate if the differences in the kinetics of overground and treadmill running are reflected in differences in the in vivo tibial strains and strain rates. The study was limited in the number of subjects because the measurements require the surgical application of a strain gauged bone staple and volunteers are not plentiful. Measurements were also limited to one site on the tibia. This site was chosen because it is the most common site of stress fractures among runners and military recruits.[2] Strain measurements were only axial and were made at 11 km/h, which is a moderate jogging pace.

Stress fractures and other overuse injuries are common occurrences in overground runners.[1] High bone strains and strain rates that occur during running contribute to the cause of stress fracture.[4–6] Tibial stress fractures are the most commonly occurring stress fracture in overground runners.[2] There are no parallel epidemiological data for treadmill runners in the literature. In this experiment very significant differences between the strain and strain rates during the two types of running were found. Tension and compression strains and strain rates were found to be 48–285% higher during overground running than during treadmill running. The substantially higher tibial strains and strain rates found in this experiment during overground running indicate that overground runners are at higher risk of tibial stress fracture than treadmill runners.

It has been shown in animal models that high strain and strain rates are likely to activate bone formation.[14 15] It is also thought that exercises that change the usual strain distribution that occur in a bone are likely to serve as osteogenic stimuli.[16 17] As a single element gauge was placed axially on the tibia, and not a rosette gauge, no measurement of changes in the strain distribution could be made. It is likely, however, that overground running, because it involves both changes in direction and pace, produces greater changes in strain distribution than during treadmill running.[5] Our experiment indicates on the basis of significantly higher strain and strain rates during overground running that this style of running is more likely to achieve tibial bone strengthening or maintenance than treadmill running.[16]

Take home message

For the person whose major concern is aerobic fitness or burning calories, treadmill running may be preferable to overground running, which has higher tibial strains and strain rates and therefore increases the risk of developing tibial stress fracture and osteoarthrosis of the knee.

We did not measure knee joint forces. There has been concern that running may lead to osteoarthrosis of the knees. Data from the Framingham study indicate that heavy physical labour is an important risk factor for osteoarthrosis of the knee in the elderly.[18] Spector *et al*[19] found that the risk for knee and hip osteoarthrosis in women is associated with weight bearing sports. They point out that it is important to determine what type and duration of weight bearing exercises are beneficial for cardiovascular and bone health without damaging the joints. However, in a retrospective study of past elite Finnish athletes, runners were not found to have a greater incidence of osteoarthrosis than a control group of non-athletes.[20] The population that did have a higher prevalence of knee osteoarthrosis was that comprising athletes who had participated in ball sports.

For the non-competitive runner what is preferable, overground running or treadmill running? The answer would seem to depend on the goals of the individual. Both can achieve cardiovascular physical fitness. Both can "burn calories" and help maintain a trim body weight. Overground running would seem to be preferable to treadmill running for increasing or maintaining bone strength.[21] Treadmill runners, however, would seem to be at less risk of developing tibial stress fractures and possibly other types of stress fractures, as well as of developing knee and hip osteoarthrosis.

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REFERENCES

1 **Brubaker CE**, James SL. Injuries to runners. *Am J Sports Med* 1974;**2**:189–98.
2 **Brunet ME**, Cook SD, Brinker MR, *et al*. A survey of running injuries in 1505 competitive and recreational runners. *J Sports Med Phys Fitness* 1990;**30**:307–15.
3 **Lanyon LE**, Hampson GJ, Goodship AE, *et al*. Bone deformation recorded in vivo from strain gauges attached to the human tibial shaft. *Acta Orthop Scand* 1975;**46**:256–68.
4 **Burr DB**, Milgrom C, Fhyrie D, *et al*. In vivo measurement of human tibial strains during vigorous activity. *Bone* 1996;**18**:405–10.
5 **Milgrom C**, Finestone A, Simkin A, *et al*. In vivo strain measurements to evaluate the tibial bone strengthening potential of exercises. *J Bone Joint Surg [Br]* 2000;**82**:591–4.
6 **Milgrom C**, Finestone A, Levi Y, *et al*. Do high impact exercises produce higher tibial strains than running? *Br J Sports Med* 2000;**34**:195–9.
7 **LaFortune MA**, Henning EM. Cushioning properties of footwear during walking: acceleration and force plate measurements. *Clin Biomech* 1992;**7**:181–4.
8 **Carter DR**, Caler, WE, Spengler, DM, *et al*. Fatigue behavior of adult cortical bone: the influence of mean strain and strain rate. *Acta Orthop Scand* 1981;**52**:481–90.
9 **Ekenman I**, Halvorsten K, Westblad P, *et al*. The reliability and validity of an instrumented staple system for in vivo measurement of local bone deformation. *Scand J Med Sci Sports* 1998;**8**:172–6.
10 **Elliot BC**, Blanksby BA. A cinematographic analysis of overground and treadmill running by males and females. *Med Sci Sports* 1976;**8**:84–7.
11 **Nelson RC**, Dillman CJ, Lagasse P, *et al*. Biomechanics of overground versus treadmill running. *Med Sci Sports* 1972;**4**:233–40.
12 **Nigg BM**, DE-Boer RW, Fisher V. A kinematic comparison of overground and treadmill runing. *Med Sci Sports Exerc* 1995;**27**:98–105.
13 **Wank V**, Frick U, Schmidtbleicher D. Kinematics and electromyography of lower limb muscles in overground and treadmill running. *Int J Sports Med* 1998;**19**:455–61.
14 **Turner CH**, Owan I, Takano Y. Mechanotransduction in bone: role of strain rate. *Am J Physiol* 1995;**269**:438–42.
15 **Mosley JR**, Lanyon LE. Strain rate as a controlling influence on adaptive modeling in response to dynamic loading of the ulna in growing male rats. *Bone* 1998;**23**:313–18.
16 **Lanyon LE**. Using functional loading to influence bone mass and architecture objectives, mechanisms, and relationships with estrogen of the mechanically adaptive process in bone. *Bone* 1996;**18**(suppl 1):37–43.
17 **Rubin CT**, Lanyon LE. Regulation of bone mass by mechanical strain magnitude. *Calcif Tissue Int* 1985;**37**:411–17.
18 **McAlindon TE**, Wilson PW, Aliabadi P, *et al*. Level of physical activity and the risk of radiographic and symptomatic knee osteoarthritis in the elderly. *Am J Med* 1999;**106**:151–7.
19 **Spector TD**, Harris PA, Hart DJ, *et al*. Risk of osteoarthritis associated with long-term weight bearing sports: a radiographic survey of the hips and knees in female ex-athletes and population controls. *Arthritis Rheum* 1996;**39**:988–95.
20 **Kettunen JA**, Kujula UM, Kaprio J, *et al*. Lower-limb function among former elite male athletes. *Am J Sports Med* 2001;**29**:2–8.
21 **Woo SL-Y**, Kuel SC, Amiel D, *et al*. The effect of prolonged physical training on the properties of long bone: a study of Wolff's Law. *J Bone Joint Surg [Am]* 1981;**63**:780–7.